

## Simulating the Gaseous Halos of Galaxies

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### Abstract.

Observations of local X-ray absorbers, high-velocity clouds, and distant quasar absorption line systems suggest that a significant fraction of baryons may reside in multi-phase, low-density, extended,  $\sim 100$  kpc, gaseous halos around normal galaxies. We present a pair of high-resolution SPH (smoothed particle hydrodynamics) simulations that explore the nature of cool gas infall into galaxies, and the physical conditions necessary to support the type of gaseous halos that seem to be required by observations. The two simulations are identical other than their initial gas density distributions: one is initialized with a *standard* hot gas halo that traces the cuspy profile of the dark matter, and the other is initialized with a *cored* hot halo with a high central entropy, as might be expected in models with early pre-heating feedback. Galaxy formation proceeds in dramatically different fashions in these two cases. While the standard cuspy halo cools rapidly, primarily from the central region, the cored halo is quasi-stable for  $\sim 4$  Gyr and eventually cools via the fragmentation and infall of clouds from  $\sim 100$  kpc distances. After 10 Gyr of cooling, the standard halo's X-ray luminosity is  $\sim 100$  times current limits and the resultant disk galaxy is twice as massive as the Milky Way. In contrast, the cored halo has an X-ray luminosity that is in line with observations, an extended cloud population reminiscent of the high-velocity cloud population of the Milky Way, and a disk galaxy with half the mass and  $\sim 50\%$  more specific angular momentum than the disk formed in the low-entropy simulation. These results suggest that the distribution and character of halo gas provides an important testing ground for galaxy formation models and may be used to constrain the physics of galaxy formation.

### 1. Introduction

It is well known that in the absence of feedback the majority of baryons in galaxy-size dark matter halos ( $M_v \sim 10^{12} M_\odot$ ) should have cooled into halo centers over a Hubble time (e.g. White & Rees 1978; Katz et al. 1992; Benson et al. 2003). In contrast, only  $\sim 20\%$  of the associated baryons in Milky-Way size halos are observed to be in a cold, collapsed form (Maller & Bullock 2004; Mo et al. 2005; Fukugita & Peebles 2006; Nicastro et al. 2007). An understanding of the feedback processes that act to solve this galaxy “overcooling” problem is a major goal of galaxy formation today. It is not known if the unaccounted baryons exist primarily as plasmas within normal galaxy halos (Maller & Bullock 2004; Fukugita & Peebles 2006; Sommer-Larsen 2006) or if they have been largely

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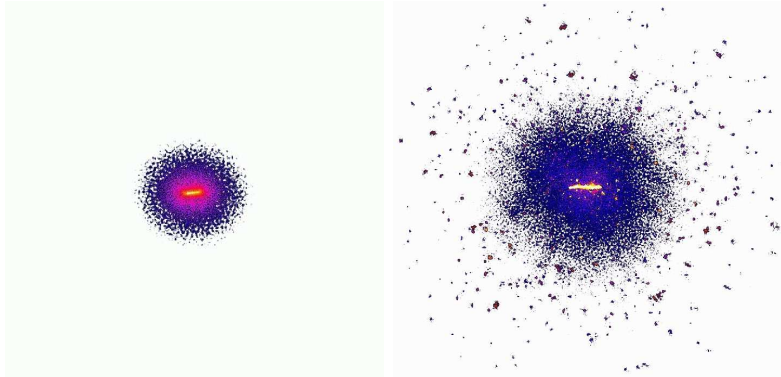


Figure 1. Renderings of the total gas density after 10 Gyr of cooling in our simulations. **Left:** results for our "standard" halo, initialized with a low-entropy cuspy hot halo. **Right:** results for the "cored" halo, initialized with a high-entropy, low-density hot halo of the same mass. In the first case, gas is concentrated around the galaxy. In the second case, the dense gas is more extended and distinct clouds are visible out to  $\sim 100$  kpc. The boxes are 400 kpc on a side.

expelled as a result of energetic blow-out (see, e.g., Oppenheimer & Davé 2006, for a discussion).

Observations of local X-ray absorbers (Williams et al. 2005; Fang et al. 2006), high-velocity clouds (Collins et al. 2005; Thom et al. 2006; Peek et al. 2007), and distant quasar absorption line systems (Tumlinson & Fang 2005; Kacprzak et al. 2007; Tinker & Chen 2007), suggest that a significant fraction of the missing halo baryons may reside in multi-phase, extended,  $\sim 100$  kpc, gaseous halos of normal galaxies. However, any hot gas around disk galaxies must be relatively low density in order to evade X-ray emission bounds ( $S_x < 10^{-14}$  erg cm $^{-2}$  s $^{-1}$  arcmin $^{-2}$ ; Rasmussen et al. 2006, Li et al. 2007). These results, together with the fairly high covering factors in cool clouds implied by absorption line studies ( $\sim 50\%$ ; Kacprzak et al. 2007), are suggestive of a model where normal galaxies are surrounded by extended, low-density hot ( $\sim 10^6$  K) halos that are filled with fragmented, pressure supported cool ( $\sim 10^4$  K) clouds (Maller & Bullock 2004).

Independently, models aimed at explaining the optical properties of galaxies have relied increasingly on the idea that extended, quasi-stable hot gas halos develop around massive galaxies (Kereš et al. 2005; Bower et al. 2006, Croton et al. 2006). It is suggested that these hot halos may be quite susceptible to feedback mechanisms, which could stabilize the systems to cooling and help explain the observed bimodality in galaxy properties (Dekel & Birnboim 2006). Observational probes of the gaseous halos of galaxies provide a potential means of testing these ideas. Entropy injected from feedback mechanisms will alter the density distribution of halo gas and affect associated cooling rates (and thus X-ray emission) and the distribution of cooling clouds fragmenting within the hot halos. Similarly, early feedback or *pre-heating* before the halo collapses can affect halo gas profiles in a related manner, with positive consequences for galaxy properties at  $z = 0$  (Mo & Mao 2002; Oh & Benson; Lu & Mo 2007).

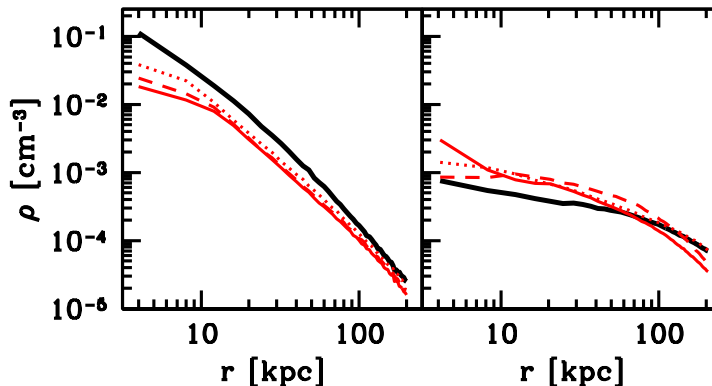


Figure 2. Evolution of the hot gas density, standard (left) and cored model (right). The hot halo of the cored model remained relatively stable for almost 10 Gyr. Line style: initial conditions (thick solid), evolution with cooling after 3 (dotted), 7 (dashed) and 10 (solid) Gyr.

## 2. Simulations

Here we present two high-resolution hydrodynamic simulations aimed studying the stability of hot gaseous galactic halos and the nature of gas cooling into galaxies. The first *standard* case is initialized with a cuspy hot halo profile that traces that of its dark matter halo. The second *cored* case is initialized with large, low-density core. The cored model has a high central entropy,  $S_0 = T_0/n_0^{2/3} \simeq 20$  keV cm<sup>2</sup>, of the type suggested in scenarios with substantial pre-heating (e.g. Mo & Mao 2002). The two simulations are identical other than their initial gas density distributions. Following Kaufmann et al. (2007), we initialize each system to be in hydrostatic equilibrium with an adiabatic equation of state within NFW (Navarro et al. 1996) dark matter halos of mass  $M_v = 10^{12} M_\odot$ . The total gas mass inside the virial radius is each case is  $10^{11} M_\odot$ . We use up to  $N = 2 \times 10^6$  gas and dark matter particles and impose initial gas angular momentum with a spin parameter  $\lambda = 0.03$ .

We track cooling in these halos using the parallel TreeSPH code GASOLINE (Wadsley et al. 2004), which is an extension of the pure N-Body gravity code PKDGRAV developed by Stadel (2001). The adopted star formation recipe is as described in Katz (1992), although we use a higher star formation efficiency factor to limit the computational expenses. We do not include any feedback associated with star formation in these exploratory simulations.

## 3. Results and qualitative comparisons with observations

As illustrated in Figures 1, 2, and 3, the different initial density distributions lead to a completely different cooling behaviors. The cuspy halo model cools

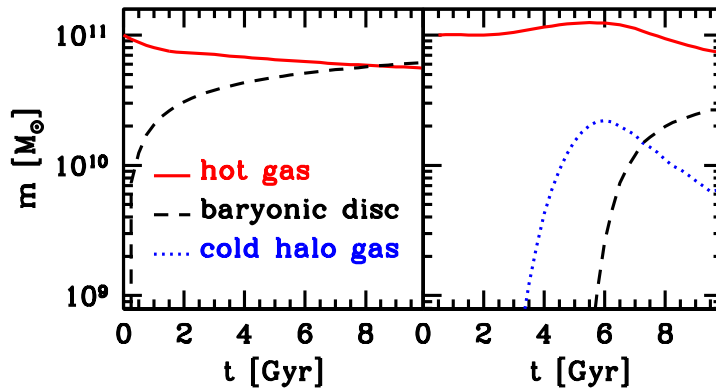


Figure 3. Mass evolution of the different gas phases, standard (left) and cored model (right). The cored model ends up with a lighter disk, warm clouds and a more massive hot gas component.

quickly from the central region and forms a massive,  $6 \times 10^{10} M_{\odot}$ , disk galaxy after 10 Gyr. Over the same period, the gas density of the cored model remains remarkably stable (Figure 2). Galaxy formation in this case proceeds after  $\sim 4$  Gyr of quasi-stability via the infall of cool, fragmented clouds as a result of the thermal instabilities (Kaufmann et al. 2006; Maller & Bullock 2004). The final disk in the cored case is significantly less massive  $\sim 3 \times 10^{10} M_{\odot}$  and also has  $\sim 50\%$  more specific angular momentum than in the standard run.

As can be seen in Figures 1 and 4, the residual baryonic halos are also substantially different in these models. The "cored" halo produces an extended  $\sim 100$  kpc distribution of fragmented, cool/warm  $T \sim 10^4$  K clouds with a total mass of  $\sim 5 \times 10^9 M_{\odot}$ , while the "standard" case yields virtually no extended cool halo.<sup>1</sup> As shown in left two panels of Figure 4, the cored run yields an extended halo of cool fragmented gas, with a fairly high covering factor, as suggested by quasar absorption system studies (e.g. Kacprzak et al. 2007). Moreover, the X-ray emission of the cored run lies within the limits mentioned above, while the standard run is  $\sim 100$  times too bright in X-ray. This difference is illustrated by the two right panels of Figure 4, where we show the X-ray surface brightness calculated using the MEKAL software package.<sup>2</sup> A more complete description will be given in Kaufmann et al. (in preparation).

<sup>1</sup>Note that we find that the final *mass* of this cool halo component is independent of our numerical resolution, as is the overall time evolution history.

<sup>2</sup>see <http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/>

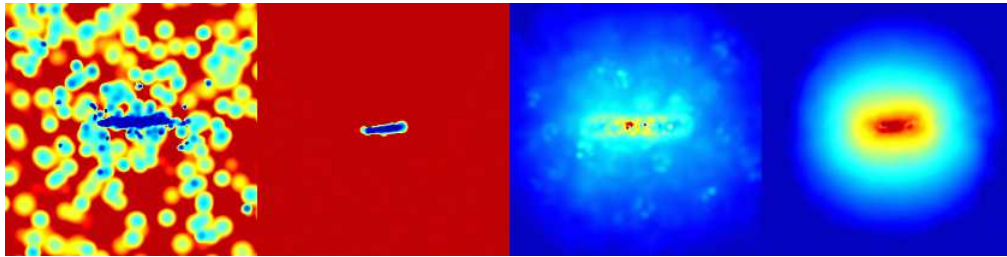


Figure 4. **Left:** Projected density of cool/warm  $T < 10^{4.4}$  K gas for the *cored* model (left) and *standard* cuspy model (right). The color map spans  $10^{18-21}$  atoms  $\text{cm}^{-2}$ . **Right:** X-ray surface brightness map for the *cored* (left) and *standard* cuspy model (right). The color map spans  $(10^{-17.1} - 10^{-12.1})$  erg  $\text{s}^{-1}$   $\text{cm}^{-2}$  arcmin $^{-2}$ .

#### 4. Summary and Conclusions

Testing the effects of different initial conditions can teach us about the types of gaseous halos that are required to match the observed distributions of halo gas around galaxies. These preliminary simulations show that a cored initial gas density profile with a high initial entropy (as expected in pre-heating scenarios) but without any other feedback can produce disk masses, cool gas distributions, and X-ray emission signals that are in better agreement with observations than a more standard cuspy halo case with low central entropy. These results suggest that the distribution and character of gaseous galactic halos provide a powerful tool for understanding the physics of galaxy formation.

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